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An update on applications of 3D printing technologies used for processing polymers used in implant dentistry

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Abstract: Polymer additive manufacturing (AM) technologies have been incorporated in digital workflows within implant dentistry. This article reviews the main polymer AM technologies in implant dentistry, as well as their applications in the field such as manufacturing surgical guides, custom trays, working implant casts, and provisional restorations.

Keywords 3D printing ● Additive manufacturing technologies ● Guided surgery ● Implant dentistry ● Polymers

Introduction

Additive manufacturing (AM) procedures provide an alternative manufacturing method in which a powder or liquid base material is built into a solid object [1-4]. The American Society for Testing and Materials (ASTM) has defined Additive Manufacturing (AM) as ‘‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [5]. The CAD data files, exported for the industry-standard exchange format, are in the Standard Triangulation Language (STL), which is a boundary representation consisting a list of triangular facets [6].

In 2008, the ASTM international committee F42 on AM technologies determined seven AM categories: stereolithography (SLA), material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination and direct energy deposition [5]. This article reviews the main AM technologies to process polymers, as well as their applications in implant dentistry, such as manufacturing surgical guides, custom trays, working implant casts, and provisional restorations. In implant dentistry, the most commonly used 3D polymer printing technologies are stereolithography (SLA) and material jetting [2,4].

In SLA technology, conceived by Chuck W. Hull, [7-9] the building platform is immersed in a liquid resin that is polymerized by an ultraviolet laser. The laser draws a cross-section of the object to form each layer. After the layer is polymerized, the building platform descends by a distance equal to the layer thickness, allowing uncured resin to cover the previous layer. This process is repeated a number of times until the printed object is built (Fig. 1A) [7-11]. Laser-based SLA 3D printing uses a UV laser to trace out the cross-sections of the object. The laser is focused with a set of lenses and reflected of two motorized scanning mirrors (galvanometer). The scanning mirror directs a laser beam at the reservoir of UV sensitive resin to cure the layer (Fig. 1A). The depth of cure, which ultimately determines the z-axis resolution, is controlled by the photo-initiator and the irradiant exposure conditions (wavelength, power, and exposure time/velocity), as well as any dyes, pigments, or other added UV absorbers [12-16].

Larry Hornbeck of Texas Instruments created the technology for digital light processing (DLP) in 1987 [17]. The DLP AM is very similar to SLA technology and is considered in the same AM category by the ASTM [5]. The main difference between the SLA and DLP is the light source, where the image is created by an arc lamp or microscopically by small mirrors laid out in a matrix on a semiconductor chip, known as a Digital Micromirror Device (DMD). Each mirror represents one or more pixels in the projected image. The number of mirrors corresponds to the resolution of the projected image [18].

A vat of liquid photopolymer is exposed to light from a projector under safelight conditions. The DLP projector displays the image of the 3D model onto the liquid photopolymer. In this system, the physical object is pulled up from the liquid resin rather than down and further into the liquid photopolymeric system. The radiation passes through a UV transparent window [18]. The process is repeated until the 3D object is built [17,18].

In material jetting technology, also known as Polyjet Printing (PP), a liquid resin is selectively jetted out of hundreds of nozzles and polymerized with ultraviolet light [12]. The UV-curable polymers are applied only where desired for the virtual design, and since multiple print nozzles can be used, the supporting material is co-deposited. Moreover, different variations in color or building materials with different properties can be designated, including the formation or structures with spatially graded properties (Fig. 1B) [19-21].

Applications of polymer am technologies in implant dentistry

1. Surgical guides

The term computed tomography surgical guide is defined as “a surgical procedure that uses a device (surgical guide) that was additively manufactured from a digital file of the cone beam computed tomography (CBCT)” [22-24]. The digital workflow is composed of three basic phases: first, data acquisition of patient information, such as CBCT and the intraoral impression, second, digital processing of this information and the virtual planning through a specific dental CAD software [25,26]; and finally, CAM production of the surgical guide (Fig. 2A) [27-29]. Jung and coworkers [30] have categorized these guided procedures into static and dynamic systems. Static systems are those that transfer predetermined implant sites using surgical templates in the patient’s mouth. On another hand, dynamic systems communicate the selected implant positions to the operative field with visual imaging tools on a computer monitor instead of rigid intraoral surgical guides. Dynamic systems include surgical navigation and computer-aided navigation technologies and allow the surgeon to alter the surgical procedure and implant position in real time using the anatomical information available from the preoperative plan and a CT or CBCT scan based on the conditions encountered during surgery (Table-1).

AM guided surgical templates have been utilized in the static implant guided surgery workflow since 2000 [30-50]. SLA is the most common AM technology used in implant dentistry for producing surgical guides via CAD/CAM procedures [25,26,35-45]. After the fabrication of the 3D printed surgical guide, an implant sleeve is manually positioned on the surgical guide (Fig. 2A).

Different systematic reviews have been performed, evaluating the accuracy of static implant placement procedures [30,41-49]. Jung et al [30] performed a systematic review that analyzed the accuracy and clinical performance of computer technology applications in surgical implant dentistry. The results showed an annual failure rate of 3.36% (0% to 8.45%) after an observation period of at least 12 months. The meta-analysis of all the preclinical and clinical studies showed accuracy at the entry point with a mean error of 0.74 mm and a maximum of 4.5 mm, while at the apex the mean error was 0.85 mm, with a maximum of 7.1 mm.

Schneider et al [41] analyzed the dental literature regarding accuracy and clinical application in computer-guided template-based implant dentistry. Meta-regression analysis revealed a mean deviation at the entry point of 1.07 mm (95% CI: 0.76–1.22 mm) and 1.63 mm at the apex (95% CI: 1.26–2 mm). No significant differences between the studies were found regarding the method of template production or template support and stabilization. Early surgical complications occurred in 9.1% of studies. Early prosthetic complications occurred in 18.8%, and late prosthetic complications in 12%. In six clinical studies with 537 implants, mainly restored immediately after flapless implantation procedures, implant survival rates were 91% to 100% after an observation time of 12 to 60 months.

In 2012, Van Assche and colleagues [43] evaluated the accuracy of implant placement through static guided systems and osteotomies without implant placement. The mean deviation of implants inserted using guided surgery techniques was 1.09 mm at entry with a mean deviation of 1.28 mm at the apex and 3.9° in angulation. The mean deviation at the entry point in vivo was 0.87 mm (SE

0.11, max 3) when the implant placement was guided and 1.34 mm (SE 0.06, max 6.5) when unguided. The mean respective deviation at the apex of the implants was 1.15 mm (SE 0.12, max 4.2) and 1.69 mm (SE 0.08, max 6.9) when unguided. The mean deviation in angulation was 3.06 ° (SE 0.27, max 15.25) when the implant was guided and 5.6° (SE 0.4, max 24.9) when unguided. Deviation parameters (entry, apical, and angle) were significantly lower for implants, which were guided during the insertion. The review also illustrates that one has to accept an inaccuracy of 2 mm, seemingly large at first view, but is clearly lower than that for non-guided surgery. The authors also concluded that a reduction of the accuracy below 0.5 mm seems extremely difficult based on the systematic review performed.

Tahmased et al [44] also developed a systematic review analyzing the accuracy of static guided surgery systems. The mean failure rate reported was 2.7% (0% to 10%) where the implant survival rate was 97.3% after an observation period of at least 12 months. The accuracy at the entry point had a mean error of 1.12 mm, with a maximum of 4.5 mm, while at the apex the mean error was 1.39 mm, with a maximum of 7.1 mm.

Moraschini et al [45] evaluated the implant survival rate, changes in marginal bone level, and complications associated with guided surgery for the treatment of fully edentulous patients with a follow-up of longer than 1 year. The analysis of the studies included in this systematic review showed that the mean cumulative survival rate was 97.2% (SD 3.49), with a mean of marginal bone loss of 1.45 mm over 1-4 years of follow-up. However, associated complications such as implant loss, prosthesis or surgical guide fractures, and low primary stability were often found.

In 2017, Gallardo et al [47] evaluated the accuracy of guided surgery when using different supporting tissues (tooth, mucosa, or bone) for AM templates. This meta-analysis showed that bone-supported guides provided lower accuracy than did the tooth and mucosa-supported guides. On the other hand, the overall meta-analysis showed no significant difference between tooth and mucosa-supported guides in any of the variables: angle deviation, deviation at the entry point, and deviation at the apex.

A recent systematic review and meta-analysis analyzed and compared implant accuracy in implant patients, cadavers, and in-vitro models. Moreover, the authors also compared the accuracy of half-guided implant surgery with that of full-guided implant surgery [48]. For apical horizontal deviation, in-vitro studies (mean 0.85 mm, 95% CI 0.5–1.2) obtained more accuracy than clinical studies (mean 1.40 mm, 95% CI 1.2–1.6) and cadaver studies (mean 1.52 mm, 95% CI 1.2–1.9). For angular deviation, in-vitro studies also obtained more accuracy (mean 2.39 degrees, 95% CI 1.7–3.1) than clinical studies (mean 3.98 degrees, 95% CI 3.3–4.6) and cadaver studies (mean 2.82 degrees, 95% CI 2.0–3.6). For horizontal coronal deviation and vertical deviation, the differences were not statistically significant. Implants placed with full-guided surgery achieved greater accuracy than implants placed with half-guided surgery in horizontal-coronal deviation (1.00 mm and 1.44 mm, respectively), in apical-horizontal deviation (1.91 mm and 1.23 mm, respectively), and in angular deviation (3.13 degrees and 4.30 degrees, respectively) [48].

Accumulative errors of each step on the workflow, from data acquisition to manufacturing processes of the surgical guide and implant placement, represent the discrepancy between the planned position and the final clinical position of the implant in the patient's mouth [50]. From additive manufacturing processes, several factors may affect the accuracy (precision and trueness) of the surgical guide such as laser speed, intensity, angle and building direction [51-56], number of layers [51], software [56], shrinkage between layers [54], amount of supportive material [53] and post-processing procedures. Few published studies have analyzed the accuracy of the surgical guide manufacturing process [57-62]. It has been reported as a deviation due to the inaccuracy of surgical template fabricated by SLA less than 0.25 mm [57].

Matta et al [58], from the same virtual planning based on a scanned plaster model, compared the accuracy of the implant sleeve from the conventional thermo-formed and a 3D printed surgical guides. Both manufacturing processes varied significantly with respect to the 3D positioning of the implant sleeve, as well as its angle. The average deviation ranged from 0.266 mm to 0.864 mm and 3.5 degrees for the angle. The largest deviation in all spatial directions was found in the Z-axis (0.594 mm).

Somacal et al [60] analyzed the accuracy of two 3D printers with 2 different AM technologies (material extrusion and DLP technologies) when fabricating the surgical guide for 8 patients. The material extrusion 3D printer provided could not be placed on the working casts, indicating physical inaccuracy. However, the material extrusion technology is rarely used to manufacture surgical guides.

Furthermore, different polymer materials are available to manufacture surgical guides through various AM technologies and 3D printers (Table-2). These materials present different mechanical properties, however there is no consensus or recommendations regarding the minimum criteria to ensure sufficient quality and precision of 3D-printed surgical guides.

2. Custom trays

The incorporation of polymer 3D printing technologies allows the replacement of certain manual prosthodontic operations such as the fabrication of a custom tray by digital methods improving the efficiency and accuracy of production. Additive methods provide a more economical manufacturing process where the digital design of the custom tray offers an efficient method to control the space for the impression material or the extensions of the custom tray (Fig. 2B) [2,4,61-66].

Recent publication described a technique for a complete arch implant impression procedure where the metal splinting framework and the polymer custom tray were manufactured using AM technologies [66]. The main advantage of this method is the complete control of the space left for the impression material around each implant impression abutment.

3. Working casts

AM technologies have improved the connection in the digital workflow between the intraoral scanning acquisition and manufacturing processes of dental prostheses. These casts are most commonly manufactured using SLA, DLP and material jetting AM technologies (Fig. 2C) [4]. Its accuracy is the accumulation of the distortion from the acquisition methods, the parameters determined on the design software, and the CAM processes to manufacture the casts [4].

The major conceptual difference between the 3D printed AM models and the conventional dental stone (CDS is the design of the implant analogs. On the CDS models, the implant analog is designed as a retentive element so that it does not move when pouring the dental implant impression. Additionally, when manufacturing a 3D printed AM model, the digital implant analog is placed after the model is manufactured, and consequently is retrievable from the cast [67].

Different studies have analyzed the accuracy of AM casts [67.74], however, only one study analyzed the accuracy of the implant analog position on the AM cast. Revilla-León et al [67] compared the duplication capabilities of a completely edentulous cast with six implant analogs using AM technologies and conventional procedures. On the AM group, the cast was digitized using a laboratory scanner and manufactured using 4 different AM technologies; in the conventional group, a 3D-printed metal splinting framework with a 3D-printed custom tray and polyether material was used to duplicate the cast. A coordinate measuring machine was used to analyze the implant analog position on the x, y and z-axis. The mean distortion (μm) ranged from 22.7 to 74.9, 23.4 to 49.1, and 11.0 to 85.8 in the x-, y-, and z-axes, respectively. All the AM methods were able to be accurately duplicated with no significant difference with the conventional method. Moreover, the 2 AM technologies analyzed obtained significantly better accuracy on the x-axis (22.7) ($p=0.037$) and z-axis (11.0) ($p=0.003$) compared with the conventional group (x-axis: 37.1; z-axis: 27.62).

4. Provisional restorations

AM technologies can be also selected to manufacture implant-supported provisional restorations [4]. However, there is a need for studies regarding the mechanical properties and long-term behavior of these polymer materials fabricated using 3D printing technologies.

Limitations and future perspectices

3D printed technologies are an emerging manufacturing methodology that provide a cost-effective solution in implant dentistry; however, dentists and dental technicians have to undergo training to understand and overcome the learning curve. Moreover, future studies are needed to analyze newly 3D printing dental materials, along with their accuracy, reproducibility, and clinical outcome over time and throughout function.

Summary

The additive manufacturing (AM) technologies currently available to process polymers are a reliable option in dentistry, however future studies are needed to evaluate their accuracy, reproducibility, and clinical outcome over time and function.

Conflict of Interest

The authors did not have any conflict interest, financial or personal, in any of the materials described in this study.

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Captions to legends:

Tables:

Table 1 Examples of some static and dynamic guided implant placement systems available in the market.

Table 2 Summary of some AM providers for the fabrication of 3D printed surgical guides.

Table 3 Mechanical properties of some 3D printed surgical guide material.

Table 4 Hazards identification of some 3D printed surgical guide material.

Figures:

Figs. 1a-b Main polymer additive manufacturing technologies with dental applications in implant dentistry. **a)** Stereolithography AM technology scheme. Illustration courtesy of Additively.com, **b)** Material jetting 3D printing technology scheme. Illustration courtesy of Additively.com.

Figs. 2a-c Polymer 3D printing applications examples in implant dentistry **a)** Printed surgical guide, **b)** Open custom tray for implant impression technique. **c)** Working cast for an implant-supported protheses.

TABLES

Table 1 Examples of some static and dynamic guided implant placement systems available in the market.

MANUFACTURER	SOFTWARE/SYSTEMS	GUIDED SYSTEM TYPE
3Shape	Implant Studio	Static
360imaging	360dps	Static
Anatomage	InVivo 6 Anatomage Guide	Static
AstraTech Dental	Facilitate	Static
BioHorizons	VIP 3	Static
Biomet 3i	Navigator	Static
BlueSky Bio	BlueskyPlan	Static
CyberMed	OnDemand3D In2Guide	Static
The dental imaging company	Navident	Dynamic
Materialise	Simplant	Static
Nobel Biocare	NobelClinician NobelGuide	Static
Sirona	SICAT	Static
Straumann	CoDiagnostiX	Static
Swissmeda AG	Smop	Static
X-Nav Technologies	X Guide	Dynamic

*NA: Not available
**USP: U.S. Pharmacopoeia

Table 2 Summary of some AM providers for the fabrication of 3D printed surgical guides.

MANUFACTURER	MATERIAL	BIOCOMPATIBILITY
3D Systems	VisiJet M3 StonePlast	CE-Certified USP** Plastic Class VI
BEGO	VarseoWax SG	Class I
DentalMed	3Delta Guide	Class I
Detax	Freeprint splint	Class I, IIa
Dreve	FotoDent Guide	NA*
EnvisionTec	E-Guide tint	Class I
	Clear Guide	USP** Plastic Class VI
FormLabs	Dental SG Resin	Class I
NexDent	NexDent-SG	Class I, CE-Certified
Shera	SHERAprint Ortho Plus	Class IIa
	SHERAprint Ortho Plus UV	
Stratasys	MED610 (Clear-Bio)	Up to 24h certified for mucosal-membrane contact USP** Plastic Class VI

*NA: Not available

Table 3 Mechanical properties of some 3D printed surgical guide material.

MATERIAL	COLOR	WAVELENGTH (nm)	FLEXURAL STRENGHT (MPa)	MODULUS ELASTICITY (MPa)	ELONGATION AT BREAK (%)	HEAT DISTORTION TEMPERATURE (C)	STERILIZATION
VisiJet M3 StonePlast	Natural	405	51	1.850	17	56	NA*
VarseoWax SG	Transparent blue	405	≥50	≥1.500	NA*	NA*	NA*
3Delta Guide	Transparent	385	NA*	NA*	NA*	NA*	NA*
Freeprint splint	Clear transparent	405 378-388 (UV)	NA*	NA*	NA*	NA*	NA*
FotoDent Guide	Clear transparent	385	≥90	≥1.900	≥9	NA*	NA*
	Clear transparent	405	≥75	≥1.700	≥10-15	NA*	NA*
E-Guide tint	Translucent orange	365-405	80	2.000	NA*	NA*	134°C Max. 5 min
Clear Guide	Clear transparent	365-405	88.4	1.920	6.62	NA*	NA*
Dental SG Resin	Transparent orange	(315 – 400 nm) + UV-Blue (400 – 550 nm)	50	1.500	NA*	NA*	121°C for 15 minutes, 134°C for 6 minutes, or 138°C for 3 minutes
NexDent-SG	Translucent orange	Blue UV-A + UV-Blue 315-400 + 400-550	≥80	≥2.000	NA*	NA*	134°C Max. 5 min
SHERAprint Ortho plus	Clear transparent	405	79	1.900-2.100	NA*	NA*	Do not use heat-based methods for disinfection of sterilization
SHERAprint Ortho plus UV	Clear transparent	385					121°C Max. 15 min
MED610 (Clear-Bio)	Clear	200-400	75-110	2.000-3.000	10-15	NA*	132°C Max. 4 min

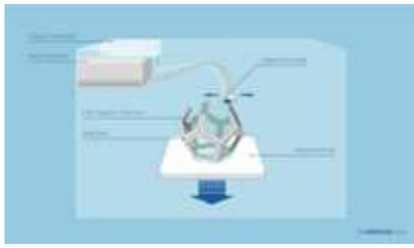
*NA: Not available

Table 4 Hazards identification of some 3D printed surgical guide material.

MATERIAL	EYE IRRITATION	ORGAN TOXICITY SIGLE EXPOSURE (STOT SE)	SKIN IRRITATION	SKIN SENSITIZATION	AQUATIC ENVIROMENT LONG TERM HAZARD
VisiJet M3 StonePlast	Category 2	Category 3	Category 2	Category 1	Category 3
VarseoWax SG	Category 2	Category 3	Category 2	Category 1	Category 4
3Delta Guide	NA*	NA*	NA*	NA*	NA*
Freeprint splint	NA*	NA*	NA*	NA*	NA*
FotoDent Guide 385nm	Category 2A	NA*	NA*	Category 1	Category 4
FotoDent Guide 405nm	Category 2A	NA*	NA*	Category 1	NA*
E-Guide Tint	NA*	NA*	NA*	Category 1	Category 4
Dental SG Resin	NA*	NA*	NA*	Category 1	Category 2
NexDent-SG	NA*	NA*	NA*	Category 1	Category 4
SHERAprint Ortho Plus	Category 2	NA*	Category 2	Category 1	Category 3
SHERAprint Ortho Plus UV	Category 2	NA*	Category 2	Category 1	Category 3
MED610 (Clear-Bio)	Category 1	Category 3	Category 2	Category 1B	Category 4

*NA: Not available

Figures:


A

B

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